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Damage Mechanisms under Fretting of Self-Mated Stainless Steel (SS 316L) and Chromium Carbide Coatings

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Abstract

Fretting is of a serious concern in many industrial components, specifically, in nuclear industry for the safe and reliable operation of various component/system. Comprehensive experimental and numerical studies have been carried out to understand the mechanics and mechanisms involved under fretting conditions. Experiments were performed on a first-of-a-kind fretting machine, with the capabilities of simulating different fretting regimes under ambient and high vacuum (10^{-5}mbar) conditions and, temperatures up to 873K. Studies were made on self-mated stainless steel (SS) and stainless steel mated against coated surfaces. Chromium carbide with 25% nickel chrome binder coatings using plasma spray and High Velocity Oxy Fuel (HVOF) processes on SS were investigated in detail. As evident from the experimental studies, the initiation or nucleation of damage in self-mated SS is due to severe plastic deformation. Ratcheting has been observed as the governing damage mode under cyclic tangential loading condition. Once the crack has been initiated under ratcheting, the propagation is controlled by fatigue. The orientation of crack propagation has been observed to be governed by the contact conditions prevailing at the contact interface. Numerical analysis result shows that the propagation of the subsurface cracks is controlled by strain energy release rate.

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Keywords: fretting regimes, plastic deformation, ratcheting, strain energy release rate

1.0 Introduction

In practical applications such as nuclear industry (fuel elements, valves, steam generators, etc.) or in aeronautical industry (fan and rotor blades, shafts, etc.), small amplitude oscillations some time induces surface degradation in the form of surface cracks and /or surface wear. Such degradation has been categorized as being under fretting. The condition of fretting has been distinguished from sliding based on two major aspects. Firstly, relative velocity of the contacting bodies is very low and secondly, the surfaces are never brought out of contact.

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This results in little opportunity for the wear debris to escape from the contact interface. R.B.Waterhouse [1] first indicated the evolution of damage under fretting condition, as illustrated in Figure 1.

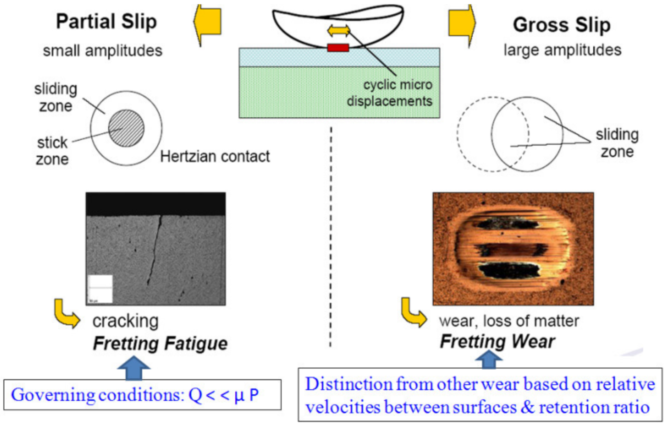

Figure-1: Illustration of fretting conditions [1].

Stainless steel (SS) is often used in nuclear industry because of its excellent mechanical properties under high temperature and irradiation environment, but on the other hand, SS is characterized as having relatively poor wear and galling resistance. In nuclear power plants (NPPs), different components move relative to each other, due to differential thermal expansion or flow-induced vibration or during loading and unloading events, and such conditions are being categorized as being under. In a Fast Breeder Reactor (FBR) the reactor core components are exposed to liquid sodium environment, which is a low oxygen environment. Experiments under liquid sodium are difficult and as a first step, the tests were done under vacuum condition to simulate condition in a sodium environment. Stainless steel (SS316L) is a reactor core component material used in FBRs. Chromium carbide coatings are already qualified based on the performance criteria for friction coefficients, wear rates and galling resistance, but has not been evaluated under fretting conditions[2]. Thus, self-mated SS and, SS mated against chromium carbide coatings are investigated in detail.

2.0 Experiment Details

Experiments were performed on first-of-a-kind fretting machine, with the capabilities of simulating gross sliding and seizure condition under ambient and vacuum condition. The features of the machine have been discussed elsewhere [3]. The major challenge in the design of a fretting machine is to achieve low displacement amplitude, as low as 1μm, between the contact surfaces under constant normal load. The hydraulic actuated machine works under displacement controlled mode, for any frequency between 4Hz and 120Hz, under high vacuum of 10^{-5}mbar and for temperatures up to 873K. A unique feature of the machine is the design of flexural member which provides not only high axial stiffness but also flexibility in the lateral direction. A robust control system with an efficient data acquisition system adds to the reliability of the system.

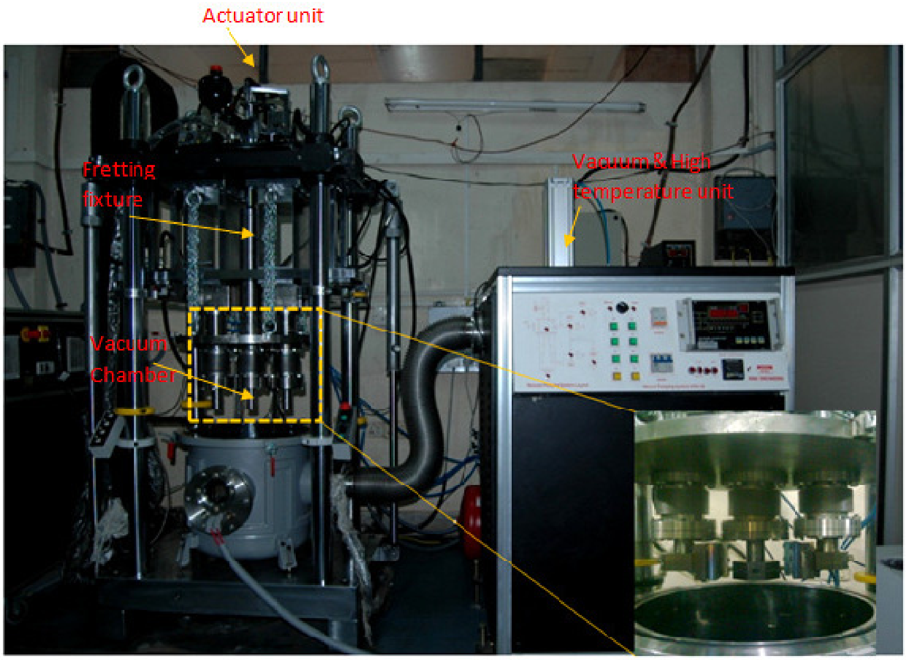

Figure-2: Experimental Set-up

Chromium carbide with 25% nickel chrome binder coatings using plasma spray and high-velocity oxy-fuel (HVOF) processes on stainless steel were investigated. The choices of the coating processes have been made such that the substrate must be maintained in a particular metallurgical condition. The effect of normal load, displacement amplitude, environment conditions and stress field were critically examined. The mechanical responses were correlated with damage observed from the scar profile and the micrographs. The details of the studies have been discussed elsewhere [4].

Contact conditions prevailing at the interface were identified based on variation of coefficient of friction (COF) with number of cycles, running condition fretting loops, and total energy dissipation at the contact interface. Gross sliding conditions have been observed under normal load of 70N and 250N and displacement amplitude in the range of 50µm to 200µm, except for normal load of 250N and displacement amplitude of 50µm. Frictionally constrained conditions have also been investigated at normal load of 600N and for displacement amplitude in the range of 25µm to 200µm. Constant shear force with number of cycles and dependence of friction force on displacement amplitude were observed as the typical characteristics of frictionally constrained bodies.

3.0 Results and Discussion

Responses under various contact conditions have been discussed elsewhere [3-5]. Higher value of COF observed for self-mated SS, compared to SS versus coated surface, which has been attributed to the existence of strong adhesion prevailing at the contact interface. It has been observed that adhesion is effective under certain conditions and depends on mechanical variables such as normal load, interfacial tangential displacement, characteristics of the contacting bodies and most importantly on the environment conditions. In order to simulate adhesion as the governing mechanism, all these variables need to be controlled with in specified limits. For example, under high normal load the surfaces of the contacting bodies come in close contact where strong inter atomic forces comes in to play. Inter atomic forces of attraction begin to felt at distance anywhere between 10^{-4} and $5X10^{-4}$µm [6]. In addition to the normal load, if a tangential force is applied then there is the possibility of the junction growth as explained by Tabor [7]. Junction growth is accompanied by plastic deformation at the contact interface, which further adds to adhesion. The plastic deformation of the contacting bodies depends on the material hardening properties. Mokhtar et al [8] correlates the physical properties of the metals with the frictional behavior and concluded that strong adhesion occurs in the material having low melting, boiling and re-crystallization temperature. Thus, it can be inferred that an increase in the mechanical properties such as, elastic modulus, hardness and resistance to plastic flow reduces adhesion at the contact interface.

Damage mechanisms involved in self-mated stainless steel and coated surfaces mated against stainless steel have been summarized in Figure 3. As evident from the experimental studies, there is initiation or nucleation of damage due to severe plastic deformation. A textured micro structure at the crack nucleation site was found aligned in the direction of cyclic loading. Further, numerical analysis considering fully stick condition at the contact interface quantifies the plastic strain variation under tangential cyclic loading. The maximum plastic strain has been observed at the contact edge, and the accumulation of the normal plastic strain in each cycle resulted in ductile fracture. Thus, ratcheting has been observed as the governing damage mode under cyclic tangential loading condition. Further, it has been observed that under strong adhesion and low normal load, the damage can be more intense beneath the contact interface. The damage beneath the contact interface intensified to a level that shear strength or cohesive strength of the material becomes less than the interfacial shear strength.

Once the crack has been initiated under ratcheting, the propagation is controlled by fatigue. Fatigue striations of constant wavelength (1μm) at the contact edge indicate the propagation of cracks under fatigue action. The orientation of crack propagation has been observed to be governed by the contact conditions prevailing at the contact interface. At low normal load or under gross sliding condition, cracks were found parallel to the surface, whereas, under high normal load or under stick condition, multiple parallel cracks were found inclined at an angle between 45^{o} to 54^{o} to the surface.

Plasma-coated surface shows damage in the form of brittle fracture of the coating, mostly in the annular region. It is believed that due to limited ductility or the brittle nature of coated surfaces, tensile stresses at the trailing edge governs the damage. HVOF-coated surface shows transfer of stainless steel pin material to the hard coated surface under the plowing action and, thus, the governing damage mechanism is abrasion.

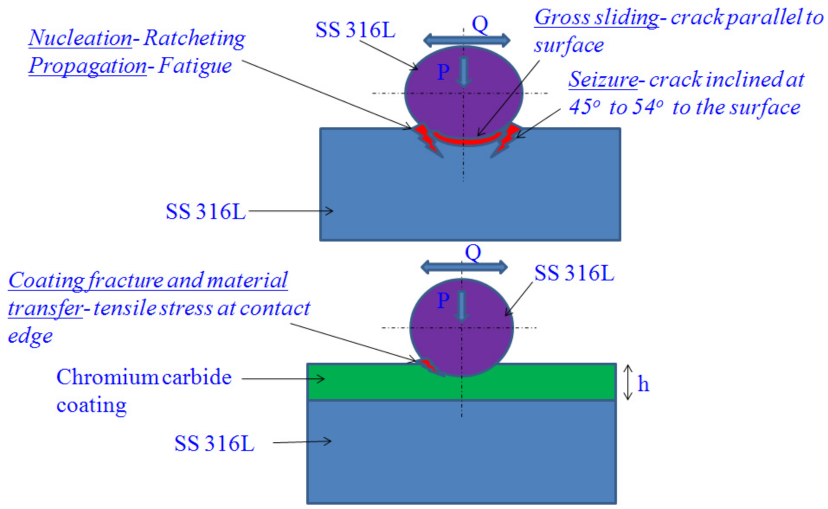

Figure-3: Damage mechanisms involved in (a) self-mated SS (b) coated surfaces. [Note: h is the coating height]

The existence of stick-slip condition has been observed under high normal load and investigated in detail. Two distinct regions, viz., center stick region and annular micro slip region were observed and their existence has been attributed to junction growth. Junction growth may occur under normal and tangential loading due to plastic flow of the material which results in an increase of real area of contact at contact interface [7]. Under tangential cyclic loading, the variation in the contact area would also be cyclic in nature. The cyclic variation may give rise to micro slip in the annular region of the contact interface, and thus, finally results in two distinguishable regions. Further, it has also been observed that interfacial microslip in the annular region also leads to the material transfer between the contacting bodies.

Numerical analysis responses show that higher shear strain energy density at the surface and in the subsurface region controls the nucleation of damage under both partial slip and gross sliding conditions. Under gross sliding condition, the damage is more probable at the surface whereas under partial slip condition the damage may nucleate in the subsurface region. Further, the studies show that the propagation of the subsurface cracks is controlled by normalized strain energy release rate. The component of normalized strain energy release rate which favors the crack propagation is referred as crack propagator energy (CPE). The availability of CPE depends on coefficient of friction and contact conditions prevailing at the contact interface.

4.0 Conclusion

Paper discusses mechanics and mechanisms involved in the degradation processes of self-mated stainless steel and chromium carbide with 25% nickel chrome binder coatings using plasma spray and high-velocity oxy-fuel (HVOF) processes on stainless steel under fretting conditions.

Fretting damage involves adhesion, plastic deformation and material transfer. Adhesion at the contact interface has been observed as a strong function of normal load, displacement amplitude, characteristics of contacting surfaces, and environment conditions. Similar materials show good adhesion. The intensity of adhesion depends on the normal load, and more strongly on the relative displacement amplitude at contact interface. Strong adhesion results in surface degradation in the form of plastic deformation, fracturing of the surface, and material transfer. For materials with good ductility it has been observed that intense plastic deformation leads to initiation/nucleation of cracks that propagates under fatigue. Further, adhesion at the contact interface and instantaneous cohesive strength of the contacting bodies dictates the occurrence of material transfer. Plasma-coated surface shows damage in the form of brittle fracture of the coating, mostly in the annular region. It is believed that due to limited ductility or brittle nature of coated surfaces, tensile stresses at the trailing edge governs the damage.

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